

# Weak radiative hyperon decays: questioning the basics

P. Żenczykowski <sup>a</sup>

<sup>a</sup>Institute of Nuclear Physics,  
Radzikowskiego 152, 31-342 Kraków, Poland

Main theoretical approaches to weak radiative hyperon decays are briefly reviewed. It is emphasized that only approaches with great predictive power should be seriously considered when seeking a resolution of the puzzle presented by observed large negative asymmetry  $\alpha(\Sigma^+ \rightarrow p\gamma)$ . In such cases, asymmetry in the  $\Xi^0 \rightarrow \Lambda\gamma$  decay is always large while its sign is positive (negative) if Hara's theorem is violated (satisfied). Measuring this asymmetry is therefore crucial for determining whether the large value of  $\alpha(\Sigma^+ \rightarrow p\gamma)$  is due to large SU(3) breaking or to some deeper reason. Some arguments suggesting that violation of Hara's theorem might be a feature of Nature, and hints as to its possible origin are also given.

## 1. INTRODUCTION

Weak radiative hyperon decays (WRHD's) present a yet unsolved problem in low-energy physics of hadronic weak interactions. The issue first appeared in 1969 when measurements of the  $\Sigma^+ \rightarrow p\gamma$  decay asymmetry [1] gave  $\alpha(\Sigma^+ \rightarrow p\gamma) = -1.0^{+0.5}_{-0.4}$ . This value was not in agreement with expectations based on Hara's theorem [2], according to which the asymmetry in question should be small. Problems with Hara's theorem have plagued the issue of WRHD's ever since.

Hara's theorem states that the parity-violating amplitude  $A$  for the  $\Sigma^+ \rightarrow p\gamma$  (and  $\Xi^- \rightarrow \Sigma^-\gamma$ ) decay should vanish in exact flavor SU(3). In reality, SU(3) is broken of course. However, if the parity-conserving amplitude  $B$  is not small ( $A \ll B$ ), one expects the asymmetry  $\alpha = 2AB/(A^2 + B^2) \approx 2A/B$  to be small (i.e. not larger than ca  $\pm 0.2$ ). The theorem follows if hadrons are described by an SU(3)-symmetric gauge- and  $CP$ -invariant local field theory. Although these assumptions (with the exception of SU(3), of course) are fundamental, one should note here that the very year the theorem was proved (1964), significant changes in our knowledge about these assumptions occurred. Thus, 1) it was proposed that SU(3) should follow from the underlying quark model, 2) violation of CP invariance was experimentally observed, and 3) the first paper pinning down the nonlocal nature of quantum physics appeared. These changes should be kept in mind when considering possible theoretical reasons for the experimentally found departure from expectations based on Hara's theorem.

At present, we know that asymmetry in the

$\Sigma^+ \rightarrow p\gamma$  decay is large. The PDG average [3] is  $\alpha(\Sigma^+ \rightarrow p\gamma) = -0.76 \pm 0.08$ , with two main experimental results contributing equal to  $-0.86 \pm 0.13 \pm 0.04$  [5], and  $-0.72 \pm 0.086 \pm 0.045$  [6] respectively. Therefore, the situation is quite disturbing since with one baryon in the initial state and one baryon in the final state (and thus lacking strong interactions in the final state), the WRHD's are fairly clean transitions, similar to the semileptonic ones or to magnetic moments. With the only WRHD-specific complication being joint appearance of weak and electromagnetic interactions, a fairly precise theoretical description of WRHD's should be then possible.

## 2. SIZE OF DATA BASIS AND RELIABILITY OF CONCLUSIONS

Although we may sum up the experimental findings by saying that expectations based on Hara's theorem are strongly violated, we cannot draw any deeper conclusions as to the origin of the effect. In this respect the situation is similar to what might have happened if we had measured the magnetic moment of proton to be  $\mu_p \approx 2.79$  but had not known anything about magnetic moments of other ground-state baryons. Although we might have stated then that large correction to the Dirac value of proton magnetic moment is present, no conclusions concerning the *symmetric* nature of flavor-spin wave functions (and hence color) would have been possible. Drawing such conclusions requires (at the very least) measuring the ratio  $\mu_n/\mu_p$  which is  $-2/3$  ( $-2$ ) for symmetric (antisymmetric) spin-flavor wave functions. The lesson is that large asymmetry observed in the  $\Sigma^+ \rightarrow p\gamma$  decay must be analysed

Table 1

Data

Decay	Asymmetry	Br. ratio·10 <sup>3</sup>
$\Sigma^+ \rightarrow p\gamma$	$-0.76 \pm 0.08$	$1.23 \pm 0.06$
$\Lambda \rightarrow n\gamma$		$1.75 \pm 0.15$
$\Xi^0 \rightarrow \Lambda\gamma$	$+0.43 \pm 0.44$	$1.06 \pm 0.16$
$\Xi^0 \rightarrow \Sigma^0\gamma$	$-0.65 \pm 0.13^{(*)}$	$3.6 \pm 0.4$
$\Xi^- \rightarrow \Sigma^-\gamma$	$+1.0 \pm 1.3$	$0.127 \pm 0.023$
$\Omega^- \rightarrow \Xi^-\gamma$		$< 0.46$

(\*) Ref. [ 4]

together with data and theory on the remaining WRHD's, i.e.  $\Lambda \rightarrow n\gamma$ ,  $\Xi^0 \rightarrow \Lambda\gamma$ ,  $\Xi^0 \rightarrow \Sigma^0\gamma$ , as well as  $\Xi^- \rightarrow \Sigma^-\gamma$  and  $\Omega^- \rightarrow \Xi^-\gamma$ . Of these, the first three turn out to be particularly important. Present experimental data [ 3] are gathered in Table 1.

Following the successes of the description of semileptonic decays and magnetic moments with the help of one (or two) parameters in each case, one may reasonably expect that the puzzle of an apparent violation of Hara's theorem in  $\Sigma^+ \rightarrow p\gamma$  will be resolved successfully if all radiative decays are well described with the help of an approach using a very small number of parameters. In other words, we need an approach which accurately predicts experimental branching ratios and asymmetries, with errors below 20%. Description of asymmetries will provide here a particularly incisive test. When such an approach akin to the quark model description of baryon magnetic moments is available, its further and deeper analysis should be attempted.

### 3. THEORY - GENERAL

#### 3.1. Hara's theorem

By using local field theory at hadron level, Hara's theorem may be obtained as follows. The most general parity-violating electromagnetic current may be written as:

$$j_{5,kl}^\mu = j_{5,kl}^{(1)\mu} + j_{5,kl}^{(2)\mu} \quad (1)$$

where  $k, l$  are baryon indices,

$$j_{5,kl}^{(1)\mu} = g_{1,kl}(q^2)\bar{\psi}_k(\gamma^\mu - q^\mu \not{q}/q^2)\gamma_5\psi_l, \quad (2)$$

and

$$j_{5,kl}^{(2)\mu} = g_{2,kl}(q^2)\bar{\psi}_k(i\sigma^{\mu\nu}\gamma_5 q_\nu)\psi_l. \quad (3)$$

Hermiticity and CP invariance of  $A \cdot j_5$  require

$$g_{1,kl} = g_{1,lk} \quad (4)$$

and

$$g_{2,kl} = -g_{2,lk} \quad (5)$$

with  $g_{i,kl}$  real.

Hara's theorem is obtained when hadron indices  $k, l$  are replaced with  $\Sigma^+, p$ . Since no *exactly* massless hadron exists, there cannot be a pole at  $q^2 = 0$ . Consequently,  $g_{1,kl}(q^2)$  must be proportional to  $q^2$ . Therefore, real transverse photons, for which  $q^2 = q \cdot A = 0$ , interact with the  $j^{(2)}$  current only. Now, under  $s \leftrightarrow d$  interchange,  $\Sigma^+ = uus$  goes into  $p = uud$  and vice versa. Thus, in exact SU(3) we must have  $g_{2,\Sigma^+p} = g_{2,p\Sigma^+}$ . Since  $g_{2,\Sigma^+p}$  is simultaneously symmetric and antisymmetric (c.f. Eq.(5)), it must vanish. (We might have e.g.  $g_{2,kl} \propto (m_k - m_l)$ ). If, for some reason,  $g_{1,\Sigma^+p}$  were not equal to 0, Hara's theorem might be violated.

#### 3.2. Quarks

Any acceptable approach to WRHD's must take into account the fact that baryons are composites made of quarks. From the point of view of essentially any quark-inspired model, the WRHD's may be divided into two groups. The first group consists of decays arising solely from such transitions in which a single quark undergoes a weak transition and radiates a photon. This occurs e.g. for  $\Xi^- \rightarrow \Sigma^-\gamma$  and  $\Omega^- \rightarrow \Xi^-\gamma$ . The other group involves more complicated two-quark processes  $su \rightarrow ud\gamma$  as well. This group contains decays  $\Sigma^+ \rightarrow p\gamma$ ,  $\Lambda \rightarrow n\gamma$ ,  $\Xi^0 \rightarrow \Lambda\gamma$ , and  $\Xi^0 \rightarrow \Sigma^0\gamma$ .

Assuming that WRHD's are dominated by single-quark transitions, one can estimate the branching ratio of decay  $\Sigma^+ \rightarrow p\gamma$  using that of  $\Xi^- \rightarrow \Sigma^-\gamma$  [ 7]. Since the latter is experimentally very small (cf. Table 1), one calculates that single-quark transition may contribute only around 1% to the experimentally observed  $\Sigma^+ \rightarrow p\gamma$  branching ratio. Thus, it is the two-quark transition  $su \rightarrow ud\gamma$  which dominates the  $\Sigma^+ \rightarrow p\gamma$  decay. Its properties should be accessible from detailed studies of the remaining decays of the second group, i.e.  $\Lambda \rightarrow n\gamma$ ,  $\Xi^0 \rightarrow \Lambda\gamma$ , and  $\Xi^0 \rightarrow \Sigma^0\gamma$ .

#### 3.3. Theoretical conflict

Although any reasonable theoretical approach must have a built-in dominance of two-quark transitions, such approaches may still differ in various ways. The issue of *how* we take quark degrees of freedom into account lies at the origin of conflict between these approaches. Namely,

various models proposed may be classified into two groups according to whether they satisfy or violate Hara's theorem. In my opinion, models violating Hara's theorem should not be rejected immediately in view of the fact that 1) we have already learned that the assumptions upon which Hara's theorem is based, although seemingly correct for WRHD's, are not valid in Nature in general, and 2) experimental data seem to be better described by models violating Hara's theorem (cf. Tables 1,4). Among the approaches that satisfy Hara's theorem we should mention the standard pole model of Gavela et al.[ 8], the chiral perturbation theory framework [ 9, 10, 11], and the QCD sum rules approach [ 12, 13]. Hara's theorem violating approaches include simple quark-model calculations of Kamal and Riazuddin [ 14] and the combined  $VMD \times SU(6)_W$  approach of ref.[ 15, 16] and its pole-model implementation [ 17].

In order to analyze the issue of possible violation of Hara's theorem, we should be able to compare experimental asymmetries and branching ratios with their predictions in various models. In principle, models might differ not only on the issue of whether Hara's theorem is satisfied or violated (i.e. in the parity-violating amplitudes), but also in their description of the parity-conserving amplitudes.

### 3.4. Parity-conserving amplitudes

Clearly, if one wants to draw firm conclusions concerning parity-violating amplitudes on the basis of comparing theory with experiment, it is very important to use a reliable description of the parity-conserving amplitudes. Fortunately, there are no real "conflicts" among various approaches to the latter. Almost all papers agree here qualitatively, although they may differ somewhat in their numerical predictions. The most widely accepted approach is a hadron-level pole model, completely analogous to that successfully used in the description of nonleptonic hyperon decays (NLHD's). In this approach, quarks are used to find symmetry properties of two types of hadronic blocks: 1) the amplitudes of photon emission by baryons, and 2) the amplitudes of weak transitions in baryons. An alternative to that approach is to calculate the whole weak radiative parity-conserving amplitude at quark-level as one hadronic block, with no explicit intermediate hadronic poles (using for example a bag model). Predictions of such an alternative

approach do not differ qualitatively from those of the pole model. Since the pole model describes the data on NLHD's very well, and one does not expect any physical complications (but rather simplification) if the pion is replaced by a photon, it is reasonable to accept the pole model as a reliable theoretical description of the parity-conserving WRHD amplitudes.

### 3.5. Parity-violating amplitudes

As in the case of parity-conserving amplitudes, the two-quark weak radiative transition  $su \rightarrow ud\gamma$  may be described either in terms of several hadronic blocks, or as a single block. Among many papers using the first approach one should mention first and foremost the paper by Gavela, LeYaouanc, Oliver, Pene, and Raynal (GLOPR) [ 8] in which a standard pole-model description of WRHD's is developed, and which provides a basis for any subsequent discussion on WRHD's. This model satisfies Hara's theorem by construction. The first group comprises also the chiral perturbation theory approach [ 9, 10, 11], and the Hara's-theorem-violating VMD-based pole model of [ 17]. The single-block approach was used in simple quark-model calculations of Kamal and Riazuddin [ 14, 18], in the bag model [ 19], in the QCD sum rules approach [ 12, 13], and in the combined  $SU(6)_W \times VMD$  approach of refs.[ 15, 16].

## 4. SPECIFIC MODELS AND THEIR PREDICTIONS

### 4.1. QCD sum rules

QCD sum rules were applied to the description of WRHD's by Khatsimovsky [ 12] and by Balitsky et al. [ 13]. Results of their calculations are given in Table 2. One can see that  $\alpha(\Sigma \rightarrow p\gamma)$  is predicted to be positive, in complete disagreement with the data (Table 1). The negative result of ref.[ 13] was obtained only in a second attempt: the original calculation produced a positive sign (disguised as a negative one, due to a different sign convention for asymmetry). Clearly, as agreed also by Khatsimovsky [ 12], QCD sum rules do not have much predictive power.

### 4.2. Chiral perturbation theory

Attempts to describe WRHD's within chiral perturbation theory (ChPT) have not led to a resolution of the problem. Ref.[ 10] contains several free parameters but the  $\Sigma^+ \rightarrow p\gamma$  asymmetry is still predicted to be small. The analysis

Table 2

QCD sum rules: predictions

Decay	Asymmetry	Br. ratio·10 <sup>3</sup>
$\Sigma^+ \rightarrow p\gamma$	+1 <sup>(1)</sup>	0.8 <sup>(1)</sup>
	-0.85 ± 0.15 <sup>(2)</sup>	0.5 to 1.5 <sup>(2)</sup>
$\Lambda \rightarrow n\gamma$	+0.1 <sup>(1)</sup>	2.1 - 3.1 <sup>(1)</sup>
$\Xi^0 \rightarrow \Lambda\gamma$	+0.9 <sup>(1)</sup>	1.1 <sup>(1)</sup>
$\Xi^- \rightarrow \Sigma^-\gamma$	+0.4 <sup>(1)</sup>	

<sup>(1)</sup> ref.[ 12]<sup>(2)</sup> ref.[ 13], originally predicted positive

of Neufeld [ 9] contains only a small number of counterterms, and therefore has more predictive power. Using as input the data on  $\Xi^0$  radiative decays available in 1992, ref.[ 9] predicts then  $|\alpha(\Sigma^+ \rightarrow p\gamma)| < 0.2$ ,  $\alpha(\Lambda \rightarrow n\gamma) \approx -0.7$  or  $-0.3$ , and  $\alpha(\Xi^- \rightarrow \Sigma^-\gamma) \in (-0.4, +0.3)$ . The conclusion of Neufeld is that "the predictive power of ChPT is limited by the occurrence of free parameters, which are not restricted by chiral (or other) symmetries alone". In a recent paper [ 11], a new attempt to attack the issue within a chiral approach has been made. This approach is very similar to the standard GLOPR paper because it is ultimately reduced to a pole model. Therefore, it would be more appropriate to discuss it alongside ref.[ 8]. However, since the paper of ref.[ 11] misses an important contribution of intermediate  $\Lambda(1405)$  [ 20], its numerical predictions for neutral hyperon decays have to be changed. It turns out [ 20] that when this is done, one essentially recovers the predictions of ref.[ 8].

#### 4.3. Standard pole model

The standard approach of Gavela et al. [ 8] was developed along the lines of their earlier paper on NLHD's [ 21]. Ref.[ 21] described parity-violating amplitudes of NLHD's as composed of two terms: the current algebra commutator and a (vanishing in SU(3)) correction ( $\Delta P_{70}$ ) arising from  $J^P = 1/2^-$  intermediate states belonging to  $(70, 1^-)$  - the lowest-lying negative-parity multiplet of  $SU(6) \times O(3)$ , i.e. schematically:

$$A = [\dots, \dots] + \Delta P_{70}(m_s - m_d) \quad (6)$$

with  $\Delta P_{70}(0) = 0$ .

Alternatively, one might saturate the current algebra commutator with this part of contribution from  $(70, 1^-)$  which does not vanish in  $SU(3)$ :  $[\dots, \dots] = P_{70}(0)$ . In other words, instead of the decomposition made on the right-hand side of Eq.(6), one might use a pole model with  $SU(3)$

breaking appropriately included:

$$A = P_{70}(m_s - m_d) = P_{70}(0) + \Delta P_{70}(m_s - m_d) \quad (7)$$

Diagrams relevant for this model are shown in Fig.1, where  $M$  stands for  $\pi$  meson, and  $B_{k*}$  - for all allowed  $J^P = 1/2^-$  baryons from the  $(70, 1^-)$  multiplet. If one wants to reproduce results of current algebra, one has to consider *all* allowed negative parity baryons from all SU(3) multiplets in  $(70, 1^-)$ , i.e.  $\Lambda(1405)$  (a SU(3) singlet),  $N(1535)$ ,  $\Lambda(1670)$ ,  $\Sigma(1750)$  (low-lying SU(3) octet), etc.

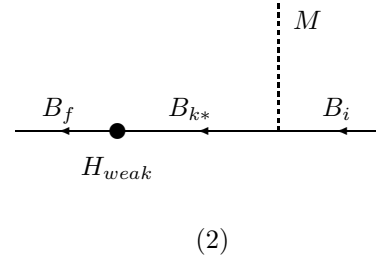
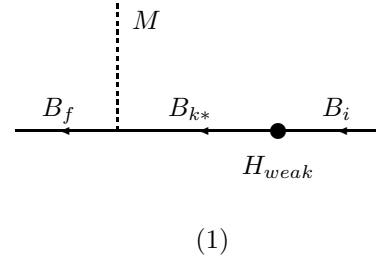


Fig.1. Baryon-pole diagrams

For WRHD's, ref.[ 8] switches to the pole model description. This should give both an analogue of the commutator term for NLHD's and the SU(3) breaking corrections.

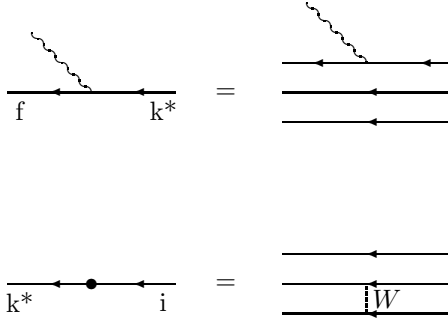


Fig.2 Hadron-level diagrams and their quark-level counterparts

The procedure applied in ref.[ 8] is as follows:

1) Use quark model to evaluate symmetry properties of the two (weak and electromagnetic) hadronic blocks in diagram (1) of Fig.1 with  $M$  now replaced by  $\gamma$  (as shown in Fig.2).

2) Determine the amplitudes for diagram (2) in Fig.1 from hermiticity, CP- and gauge-invariance.

i) the weak amplitude is antisymmetric by CP and hermiticity:  $a_{jk^*} = -a_{k^*j}$  ( $j = i, f$ ).

ii) the obtained electromagnetic coupling is identified with gauge-invariant hadron-level parity-conserving coupling

$$f_{2,fk^*} \bar{u}_{1/2+} \sigma^{\mu\nu} \gamma_5 q_\nu u_{1/2-,k^*} A^\mu \quad (8)$$

where  $f_{2,jk^*} = f_{2,k^*j}$  by CP and hermiticity.

By combining weak and electromagnetic transitions according to Fig.1, one gets

$$A \propto \sum_{k^*} \left\{ \frac{f_{2,fk^*} a_{k^*i}}{m_i - m_{k^*}} + \frac{a_{fk^*} f_{2,k^*i}}{m_f - m_{k^*}} \right\} \times \quad (9)$$

$$\times \bar{u}_f i \sigma^{\mu\nu} \gamma_5 q_\nu u_i A_\mu \quad (10)$$

For  $i = f$  (which is almost the Hara's case) we use symmetry properties of  $a$  and  $f_2$  to obtain:

$$f_{2,ik^*} a_{k^*i} = -a_{ik^*} f_{2,k^*i} \quad (11)$$

which ensures cancellation of the first and second term in Eq.(9). The sums (over  $k^*$ ) of the first and second terms can be evaluated (in SU(6)) and are given (in arbitrary normalization) in Table 3 (apart from the "−" sign requested by symmetries of  $a$  and  $f_2$ ). The prescription of the standard pole model is well defined and leads to definite predictions for the signs of asymmetries (Table 4). One obtains negative asymmetries for *all* four decays proceeding through two-quark transitions. This (−, −, −, −) pattern of asymmetries for  $\Sigma^+$ ,

Table 3  
Weights of diagrams (1) and (2) of Fig.1

Decay	Diagram (1)	Diagram (2)
$\Sigma^+ \rightarrow p\gamma$	$-\frac{1}{3\sqrt{2}}$	$-\frac{1}{3\sqrt{2}}$
$\Lambda \rightarrow n\gamma$	$+\frac{1}{6\sqrt{3}}$	$+\frac{1}{2\sqrt{3}}$
$\Xi^0 \rightarrow \Lambda\gamma$	0	$-\frac{1}{3\sqrt{3}}$
$\Xi^0 \rightarrow \Sigma^0\gamma$	$\frac{1}{3}$	0

$\Lambda$ , and two  $\Xi^0$  decays is a characteristic feature of the standard Hara's-theorem-satisfying model.

#### 4.4. "Naive" quark-level one-block calculation

In 1983 Kamal and Riazuddin (KR) calculated  $W$ -exchange accompanied by photon radiation in a simple quark framework [ 14]. The astonishing result of their calculation was an explicit violation of Hara's theorem (in the SU(3) limit). Although an agreement now exists that the calculation of ref.[ 14] is completely correct from the technical point of view ([ 22, 23, 24], the disagreement still lingers as to the origin of the offending result and, consequently, how to treat it.

Azimov [ 25] proposed a way of proceeding if one identifies the result of KR calculations with the  $j_5^{(1)}$  ( $\gamma_\mu \gamma_5$ -like) term in the full electromagnetic current (if this term is present Hara's theorem may be violated - cf. section 3.1). He noticed that in principle the perturbative KR calculation may be supplemented with a  $\gamma_5$ -dependent renormalization. Using the latter he showed that the  $\gamma_\mu \gamma_5$ -like term may be rotated away. In other words, one can "hide" the  $\gamma_\mu \gamma_5$  term of the axial current into the standard  $\gamma_\mu$  piece of the vector current. This means that the concepts of left and right are redefined in such a way that ultimately all the offending KR contribution constitutes a weak-interaction correction to the usual electromagnetic vector current.

The above idea may be applied to charged baryons only. In reality however, KR-like calculations may be performed for neutral baryons as well. It turns out that the result is again non-zero. This time, however, this result (which conflicts with Hara-like considerations) cannot be rotated away since there is no  $\gamma_\mu$  term in the vector current of neutral baryons [ 26]. One concludes [ 26]

that the origin of KR result is completely unrelated to the mechanism considered in ref.[ 25].

In my opinion (shared by Holstein [ 23]), the result of KR is due to the use of free quarks in states of definite momenta. This violates Hara's theorem because one of the theorem's assumptions is that we deal with a single object - a baryon in a state of definite momentum, and not with a collection of free quarks. This seems to mean that the KR result should be considered to be an artefact of their model, and not a feature of reality [ 23].

I think that the KR result is an artefact of their model if interpreted literally: it arises from free Dirac quarks propagating over infinite distances. However, general features of the KR approach need not be incorrect. The problem is that we still do not have a complete understanding of how unobservable quarks combine to form such composite states as hadrons. In the words of Donoghue et al. [ 27]: "The quark model was developed in the first place to explain flavor and spin properties of the observed hadrons and for this it does a good job. The spatial aspect is less well tested." It is precisely the question of position/momentum space description of hadrons as quark composites that leads to the result of KR.

#### 4.5. Alternatives - bag model and VMD

The quark model used by KR may be viewed as deficient. Let us therefore accept for the time being that its result is an artefact. Consequently, one has to replace the KR model with another, more "reasonable" approach. This new approach should still exhibit spin-flavor symmetries that form the basis of all quark model successes, but quarks should not be treated as free Dirac particles. There are two possible ways of doing this: confining quarks to a bag or using the idea of VMD combined with spin-flavor symmetries of hadrons.

Bag model calculations of Lo [ 19] show that the parity-violating amplitude of the  $\Sigma^+ \rightarrow p\gamma$  is much larger than the corresponding parity-conserving amplitude, again contradicting expectations based on Hara's theorem. Apparently, in bag model calculations Hara's theorem still seems to be violated [ 24], albeit the reasons are not clear and should be studied more closely. The bag model starts with the concept of free Dirac quarks, and then confines them. This proposes a resolution of the problem by brute force of an additional assumption and seems logically ques-

tionable to me: it assumes the answer. I much prefer using the combined  $VMD \times SU(6)_W$  approach, where questions related to quark freedom or confinement are never asked, but which "always works", although, admittedly, it is not completely clear why. The approach does not use the concept of "free quarks" but yields quark model results. Among its many successes one may mention here the successful prediction of baryon magnetic moments by Schwinger [ 28] (unlike in the constituent quark model, even the scale was predicted). It is also known that a gauge-invariant formulation of the VMD approach is possible [ 29]. An additional asset of the  $VMD \times SU(6)_W$  approach as applied to WRHD's is that essentially all parameters are set by NLHD's. Thus, we are dealing with an easily falsifiable approach of great predictive power.

The main idea of the VMD approach is as follows. One starts with the standard  $SU(3)$  symmetric model of parity-violating NLHD amplitudes (Eq.6) and uses spin-flavor  $SU(6)_W$  symmetry to obtain weak strangeness-changing amplitudes for virtual transverse vector meson (V) emission from a baryon (B). This part is calculated following the ideas of ref.[ 30]. In this way, a transverse-vector-meson analogue of the commutator term in Eq.(6) is found [ 15]. In ref.[ 30] it is identified with the  $\gamma_\mu\gamma_5$  term in the general expression for the BBV amplitude. The next step is to allow for standard VMD transition of vector meson into photon. Thus, VMD suggests that transverse photon coupling to the electromagnetic axial weak current should proceed through the  $\gamma_\mu\gamma_5$  term. Clearly, the conditions under which Hara's theorem was proved are not satisfied now, and the approach chosen to avoid the use of free quarks (and the related problems with Hara's theorem) again exhibits its violation. The parity-violating amplitudes of the VMD approach may be saturated with the contribution from intermediate  $J^P = 1/2^-$  baryons, in a way completely analogous to the case of NLHD's. The situation is similar to that occurring in the standard pole model of Gavela et al. [ 8]. There is an important difference visualised in Fig.3, though.

Table 4  
Model predictions

Decay	VMD	KR	GLOPR
$\Sigma^+ \rightarrow p\gamma$	-0.95	-0.56	$-0.80^{+0.32}_{-0.19}$
$\Lambda \rightarrow n\gamma$	+0.8	-0.54	-0.49
$\Xi^0 \rightarrow \Lambda\gamma$	+0.8	+0.68	-0.78
$\Xi^0 \rightarrow \Sigma^0\gamma$	-0.45	-0.94	-0.96

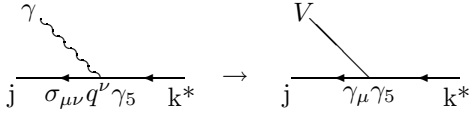


Fig.3 Photon emission in standard pole model and its vector meson counterpart

The difference is that  $f_{2,jk^*}$ , which accompanies the  $\sigma_{\mu\nu}q^\nu\gamma_5$  term (Eq.8), is symmetric under  $j \leftrightarrow k^*$  interchange, while the  $f_{1,jk^*}$  accompanying the  $\gamma_\mu\gamma_5$  vector-meson coupling is anti-symmetric. When one combines weak and electromagnetic transitions according to Fig.1 with  $M = V$  and subsequently uses VMD, one obtains

$$A \propto \sum_{k^*} \left\{ \frac{f_{1,fk^*}a_{k^*i}}{m_i - m_{k^*}} + \frac{a_{fk^*}f_{1,k^*i}}{m_f - m_{k^*}} \right\} \times \quad (12)$$

$$\times \bar{u}_f i\gamma^\mu \gamma_5 u_i A_\mu \quad (13)$$

By using symmetry properties of  $a$  and  $f_1$  one finds that the term in brackets is now symmetric under  $i \leftrightarrow f$  interchange. In other words, the two contributions in Table 3 add now rather than subtract. An immediate consequence is that 1) Hara's theorem is violated, and 2) asymmetries of the  $\Lambda \rightarrow n\gamma$  and  $\Xi^0 \rightarrow \Lambda\gamma$  are now positive. The  $(-, +, +, -)$  pattern obtained here for the  $\Sigma^+ \rightarrow p\gamma$ ,  $\Lambda \rightarrow n\gamma$ ,  $\Xi^0 \rightarrow \Lambda\gamma$ , and  $\Xi^0 \rightarrow \Sigma^0\gamma$  decays is a characteristic feature of Hara's-theorem-violating approaches. A comparison of asymmetry predictions of the VMD approach [31], the KR model [18], and the GLOPR standard pole model [8] is given in Table 4.

From the comparison of model predictions with data (Table 1) we see that at present the data favor approaches that violate Hara's theorem.

Asymmetry of the  $\Xi^0 \rightarrow \Lambda\gamma$  is crucial here. It is large in all approaches, with its sign being negative (positive) depending on whether Hara's theorem is satisfied (violated). The fact that it is almost equal in absolute value in all approaches with great predictive power is not an accident. It can be traced directly to the sign of contribution from diagram (2) and the vanishing of the contribution from diagram (1) (Fig.1 and Table 3). The data point is three standard deviations away from the standard pole model.

Information from the comparison of asymmetries is supplemented with that coming from branching ratios. So far all data are best described by the VMD model [16, 31].

## 5. SUMMARY

The problem of WRHD's is already thirty years old. Data and some models hint that Hara's theorem may be violated. The KR result should certainly be treated as an artefact if it were the only model which violates Hara's theorem. However, other quark-inspired and elsewhere well-tested models also violate the theorem, unless it is imposed by brute force of an additional assumption, foreign to quark approaches themselves. Consequently, either our present models of how photons interact with quark composites are incorrect or, as I believe, one should treat model hints seriously and try to understand what they might mean.

The issue of Hara's theorem violation may be settled experimentally. The crucial information should come from the sign of the  $\Xi^0 \rightarrow \Lambda\gamma$  asymmetry. If this asymmetry is large and negative, Hara's theorem is satisfied and one has to conclude that various hints were misleading. If, on the other hand, this asymmetry is positive, one has to conclude that violation of Hara's theorem is a feature of Nature. This would mean that at least one of the assumptions of Hara's theorem is violated.

The assumptions of CP-invariance and current conservation are satisfied explicitly in the KR paper. We have pointed out that in the KR paper violation of Hara's theorem results from the fact that in these calculations baryons consist of free quarks in plane-wave states of definite momenta. From the point of view of position space, such states contain terms with far-away quarks. It is from such configurations that violation of Hara's theorem originates. This picture hints at the assumption of locality as the one that is violated.

Hadron-level prescription (such as that of VMD) in which hadron is described by a local field may be also analysed from the point of view of position space. The net result is that CP-invariant interaction of photon with a conserved baryonic axial current does lead to the violation of Hara's theorem if the current exhibits a kind of nonlocality [32]. Thus, although the detailed origin for the violation of Hara's theorem is different in these two approaches, they both hint at nonlocality as the potential culprit. Since we know that nonlocality is a general feature of composite quantum states, the above conclusion is not in conflict with the general properties of the quantum world. However, it is certainly weird as it does challenge the generally accepted simple pictures of hadrons and photon-hadron interactions.

Since, apart from the arguments and hints presented in this talk, one can also invoke arguments of a much deeper, though usually disregarded kind, I find it quite believable that Hara's theorem may be violated in Nature.

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